FISSION TRACK DATING OF APATITES FROM CORONATION ISLAND

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By

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ABSTRACT

Fission track ages were obtained from two apatite samples from Coronation Island near the Antarctic Peninsula. These ages, 177 and 188 m.y. ($\lambda_F = 6.85 \times 10^{-17} yr^{-1}$), represent the last time the rocks cooled below approximately 100°C and probably reflect regional uplift and cooling.

INTRODUCTION

The method of fission track dating is a useful tool for the geologist as he tries to construct the geologic history of an area. Fission tracks, narrow tubes of intense damage caused by spontaneous fission of ^{238}U in apatite are highly temperature sensitive. The tracks become stable over geologic times at temperatures far below those of mineral formation. And, the ages ascertained by this method represent a cooling age for a temperature at which the mineral cooled down to a critical value for the track retention. After formation of tracks, as the temperature rises to specific levels for different minerals, fission tracks begin to anneal (repair themselves) to a point at which they are no longer revealed by chemical etching. For apatite, this temperature is low. Thus, the thermal history of rocks can be studied by fission track ages of apatites within a relatively low temperature range.

The area of study for this report is Coronation Island, part of the South Orkney Islands, east of the Antarctic Peninsula in the South Atlantic. Samples were collected from this locality by Dr. David

Elliot in 1980. Apatites from seven samples of the metamorphic basement rocks were studied by the fission track method to attain ages and information that might be indicative of cooling and uplift in the area.

GEOLOGIC SETTING

Stratigraphy

Coronation Island is largely formed of metamorphic rocks, mainly quartz-mica-schists (Mathews and Maling, 1967). The metamorphic grade of rocks at the eastern and western ends of the island is low, but it increases toward the center, reaching amphibolite facies (Thompson, 1974). The age of these rocks, while disputed, is generally considered to be Precambrian or early Paleozoic (Dalziel, 1978). At the eastern end of the island, the metamorphic basement rocks are unconformable overlain by a sequence of Cretaceous(?) sandstone and conglomerate. Doleritic dikes and sills intrude the metamorphic complex, but are not observed in the sandstone and conglomerate facies of the island. However, a comparable dike cuts the conglomerate facies on Mathews Island to the west. These dikes are now considered to be Upper Cretaceous or Tertiary (Thompson, 1971).

Structure

Thompson (1974) elaborating on field observations of D.H. Mathews, described the metamorphic complex as representing three main phases of folding. These are:

1. Formation of large north-south folds during initial metamorphism of shale-sandstone sequences to a grade varying

from albite-epidote-green schist to amphibolite facies with pre-, syn-, and past-tectonic crystallization of minerals, especially garnet, andalusite, and sphene;

2. Isoclinal folding about a north-south axes and formation of large "S-shaped" folds accompanying retrogressive metamorphism of schists in the central portion of the island; and
3. Formation of open cross folds and gentle warping on an east-west axes with very weak metamorphism and no recrystallization.

Geotectonics

The island trends in a west-east direction parallel to the sweep of the Scotia Arc, the largely submarine physiographic feature that joins South America to the Antarctic Peninsula. The arc is thought to show Late Triassic to Early Jurassic uplift of the basement complex and bending and disruption of the Andean-West Antarctic Cordillera, all related to the initial breakup of Gondwanaland (Dalziel and Elliot, 1973 and Dalziel, 1977). This is indicated by similarities in the metamorphic complexes throughout the arc, specifically the lithological and structural similarities of the South Orkney Island system and the South Shetland Island system to the west (Dalziel, 1977). Early Mesozoic folding and uplift are thought to account for different radiometric ages between the islands. In recent plate tectonic reconstructions, the two island systems are placed together at the tip of the Antarctic Peninsula (Dalziel and Elliot, 1973).

Petrographic Descriptions

The sample locations for each of the seven samples examined are shown in Figure 1. The following are petrographic descriptions of these samples.

C-1 Quartz-mica schist. No thin section available.

C-3 Porphyroblastic chlorite-quartz-albite-garnet schist. This medium grained green schist has porphyroblasts of albite and quartz, about 1-2 mm in diameter, with inclusions of albite, clinozoisite, and trails of graphite. Chlorite and small amounts of biotite interdigitate between porphyroblasts and are associated with epidote, andalusite, apatite, carbonates, and alteration products. Foliation is poorly defined.

C4-1 Biotite-hornblende-albite-garnet schist. This stongly foliated green schist is characterized by lepidoblastic laminae of biotite interupted by porphyroblasts of albite, showing elongation, and large garnets with many inclusions of albite, zircon, and epidote. Hornblende and chlorite are present in lesser amounts with accessory minerals of apatite, andalusite, epidote, and opaques.

C4-2 Hornblende-quartz-albite-garnet schist. This granoblastic green schist is predominately hornblende with smaller amounts of quartz and albite. The porphyroblasts are smaller than those of previous samples, averaging about 2 mm in diameter; they contain large

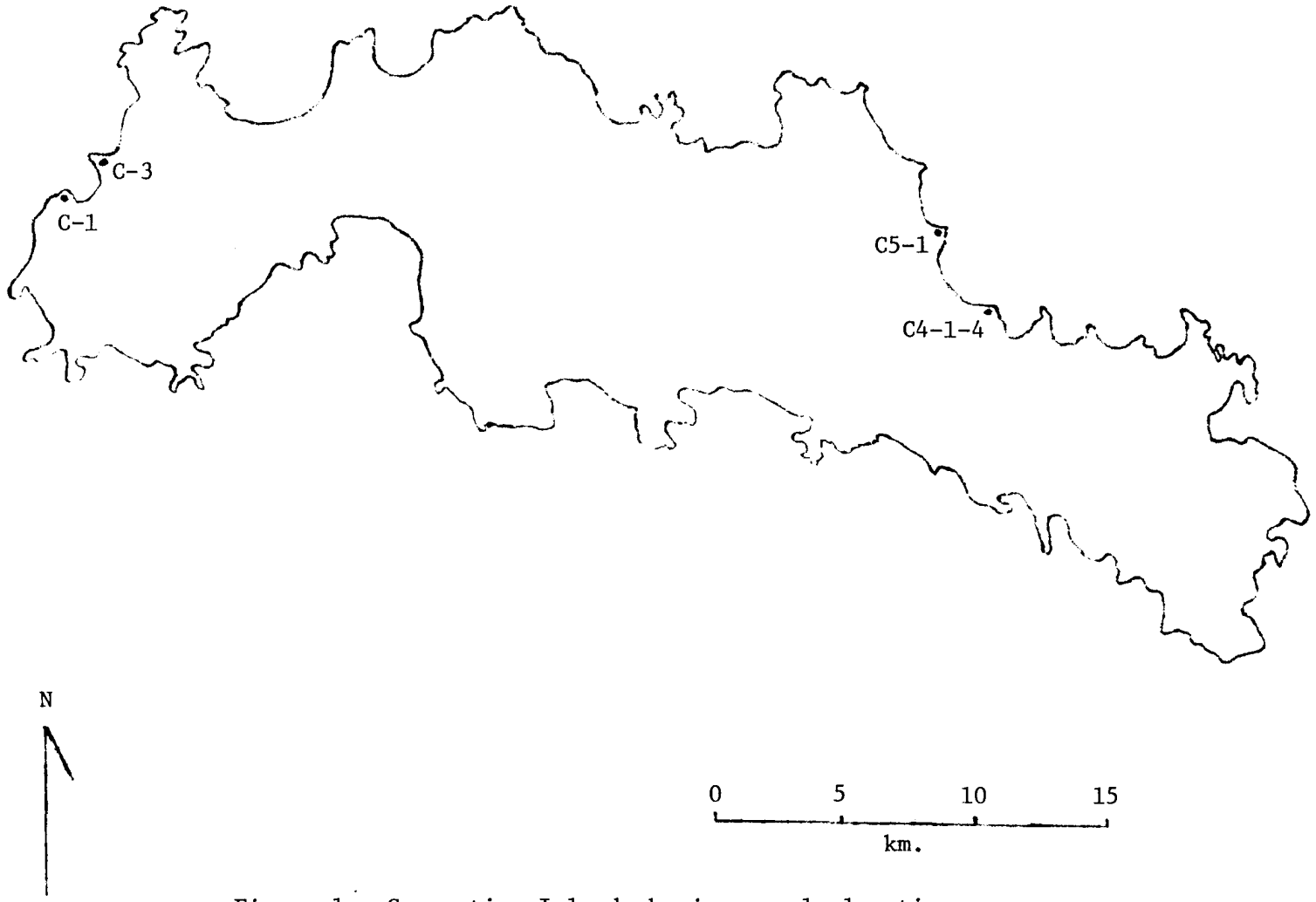

Figure 1. Coronation Island showing sample locations.

inclusions of albite. Foliation is poorly defined, but elongation of hornblende is evident. Associated minerals are apatite, andalusite, epidote, and carbonates.

C4-3 Porphyroblastic albite-hornblende-biotite-epidote-garnet schist. This brownish-green schist has abundant quartz-feldspar segregations and veins which enhance poorly defined foliation. Hornblende and epidote show elongation and parallel orientation. Garnets range from 3-5 mm in diameter and contain many inclusions. Other accessory minerals include andalusite, apatite, sphene, and opaques.

C4-4 Hornblende-albite-garnet-quartz schist. This predominantly hornblende schist shows elongation and orientation of most mineral grains with the exception of large poikotic garnets. Veins of quartz and albite are striking, but the foliation is poorly defined. Andalusite, apatite, zircon, and opaques are present as accessory minerals.

C5-1 Graphite-muscovite-quartz-albite-garnet schist. This mica schist is extremely foliated and contorted with muscovite, graphite, and lesser amounts of chlorite interdigitating around large porphyroblasts of quartz, albite, and highly altered garnets. Accessories are not easily identified, but apatite and andalusite are present.

THE FISSION TRACK METHOD

History and Theory

Fission tracks were first seen by Young (1958), and Silk and Barnes (1958). With the aid of an electron microscope, Young (1958), saw them as shallow pits in lithium fluoride crystals. Silk and Barnes (1959) saw them as fission fragment tracks in mica.

Fleischer and others (1965a) determined fission tracks to be a damage zone caused by the passing of highly charged fragments of fissioning ^{238}U through a solid, causing repulsion of positively charged ions and forcing into the lattice.

It was first discovered by Price and Walker (1962) that due to different etching rates between damaged and undamaged regions, tracks could be made visible under an optical microscope.

Fleischer and others (1965) found temperature to be the most important parameter of those which affect the stability of fission tracks. Using apatite fission tracks, they found that tracks remain stable at temperatures of less than $100^{o}C$. But with increasing temperature and heating time, causing increased atomic mobility, tracks began to anneal or repair themselves to a point at which they could no longer be revealed by etching.

Annealing characteristics of minerals have been an area of much study. Wagner and others (1977) found from annealing experiments that cooling apatite successively passes through three different temperature zones related to track stability: a zone in which no tracks are recorded due to complete track fading; a zone in which tracks are partially recorded; and, finally, a zone in which all tracks are recorded.

Zonal threshold temperatures are higher with faster cooling. Apatite fission track ages in the Central Alps, data a time when the rock temperature was at 120 ± 20°C during post metamorphic cooling processes. Likewise, Zimmerman and others (1975) found that apatite fission track ages of Northern New England do not represent the time of formation of the rocks, but the time when the area now exposed last cooled from temperatures above 100°C.

Annealing temperatures are dependant on the mineral special in which tracks form. Fleischer and others (1975) have summarized the available annealing data for a number of minerals. Annealing temperatures of coexisting minerals make it possible to define cooling histories of large bodies of rocks, and make it possible to determine uplift of an area. Wagner and Reimea (1971) found that upward increases of fission track apatite ages in the Alps reflect the uplift-time relationship for geologic past and that lateral changes reveal relative regional uplift movements.

Price and Walker (1963) first used track density for dating purposes. The track density must be high enough to be counted, but not so high that counting and recognition of individual tracks is difficult. The track density is a function of the age of the material and its uranium concentration. In very young rocks, minerals having a high concentration of uranium must be found; in old Precambrian rocks, the problem is to find minerals that have low concentrations of uranium. The fission-track-age equation is as follows (Price and Walker, 1963):

$$A = \ln\left[1 + \frac{Ps}{Pi} \cdot \frac{\lambda_D \phi_o I}{\lambda_F}\right] \frac{1}{\lambda_D}$$

where:

Ps = fossil track density

Pi = induced track density

λ_D = total decay constant for $^{238}U = 1.551 \times 10^{-10} yr^{-1}$

λ_F = decay constant for ^{238}U by spontaneous fission

$= 6.85 \times 10^{-17} yr^{-1}$ (Fleischer and Price, 1964a)

$7.03 \times 10^{-17} yr^{-1}$ (Roberts et al., 1968)

or $8.42 \times 10^{-17} yr^{-1}$ (Wagner et al., 1975)

ϕ = thermal neutron flux

o = the cross-section for neutron fission reaction of $^{235}U = 580 \times 10^{-24} cm^2$

I = the atomic ratio $^{235}U/^{238}U = 7.252 \times 10^{-3}$

There are two methods commonly used to determine Pi independent of Ps: the population method (Naesar, 1967), in which Ps is measured directly from the sample and Pi is measured from a portion of the sample that has been completely annealed and irradiated with thermal neutrons; or, the external detector method (Fleischer et al., 1964), where the sample is covered with a piece of low-uranium muscovite and irradiated, sending fission fragments into the adjacent muscovite detector. Ps is then measured from the grains and Pi from the detector.

Irratiation causes ^{235}U to fission and creates tracks proportional to the uranium concentration and thermal neutron flux. The population method can be used only if the uranium concentration of all grains is uniform, where as in the external detector method Pi is counted on the image of the grain in the detector and variations in the uranium concentration can be dealth with.

PROCEDURES

A thin section of each specimen was prepared and examined for the occurrence of apatite, sphene, and zircon. Promising samples were then coarsely crushed in a jaw crusher, pulverized in a rotary disc grinder, and then sieved using 60, 80, 100, 120 mesh U.S. standard, 8 inch diameter sieves and a Ro-tap sieve shaking apparatus.

Appropriate size fractions were then washed in tap water and dryed. They were then separated on the basis of specific gravity using bromoform (2.85), a 1/3 bromoform - 2/3 methylene iodide misture (3.17), and methylene iodide (3.33) to obtain apatite (3.1 - 3.2), zircon (4.7), and sphene (3.45). Highly magnetic portions were then removed with a hand magnet and final separation was made with a Franz isodynamic magnetic separator. Each sample was then washed in alcohol, acitone, and three times in doubly-distilled water in an ultrasonic cleaner, and dryed.

Nine of eleven samples were determined to contain apatite, zircon, and/or sphene by thin section study. After heavy liquid separation, these minerals were extremely difficult to identify due to lack of any definitive grain form. Seven samples yielded apatite. No appreciable amounts of zircon or phenes could be obtained. Final purification was difficult with apatite, andalusite, and in two samples, muscovite, being hard to separate. Final samples ranged from 50-70% pure.

The mounting procedures were generally the same as those described by Naeser (1978). Approximately 100 grains of apatite were poured onto a clean teflon mounting block between two thin pieces of cardboard.

Four or five drops of heated epoxy were then placed on grains. A labelled glass slide was placed on the epoxy-grain mix with the ends of the slide resting on the cardboard to give the mount the proper thickness - approximately 1.6 mm. The mounts were allowed to dry for twenty-four hours and then removed from the mounting block with a spatula.

Next the samples were ground on a Buehler Handiment II roll grinder using 240, 320, 400 and 600 grit sand papers to expose the 4π geometry fission tracks.

Samples were then polished to a six micron surface and finally to a one micron surface using a Hilquist lap with P.S.A. backed nylon and six and one micron diamond paste. Naeser suggests microcloth, but a lower relief surface is produced in a shorter amount of time using less diamond paste and diamond extender fluid with the P.S.A. backed nylon (Kunk, verbal communication).

Samples were etched in 7% nitric acid (by weight) for 30-50 seconds at room temperature. Checks for proper etching were made under a binocular scope at 1250X. Samples were then removed from the slide and washed in mild detergent and rinsed in distilled water.

Muscovite detectors, 0.05 - 0.1 mm thick, were cut into shapes so that their position on the mount would be apparent. Cut detectors were first placed on double stick tape attached to the lab bench, then cleaved to produce a pristine surface. The detectors were then attached to the mount with scotch tape with the pristine cleavage surface facing the grain mount.

For the population method, 200-300 grains of each sample were packaged in labelled aluminium foil and heated in an oven at 500°C for four hours to anneal all fission tracks.

To measure the thermal neutron flux during irradiation, N.B.S. srm 962 & 963 fission track glass standards were used as flux monitors. Two irradiated glasses of 1 ppm and 50 ppm uranium concentrations and two unirradiated glass also of 1 ppm and 50 ppm uranium concentrations were ground and polished as above. The two irradiated glasses were stored for later use. The unirradiated glasses had muscovite detectors attached as mentioned above.

Samples were then loaded into a polyethylene container with the 50 ppm N.B.S. Unirradiated glass on bottom, its muscovite detector upward, then any sphene or zircon samples on top of the glass, followed by the apatite samples. The 1 ppm N.B.S. unirradiated glass with the muscovite detector downwards was placed in the tube last. The location of each sample in the container was recorded as well as the thickness of each. Extra space in the container was filled with tissue before taping the package shut.

The package was then irradiated for six hours in the Triga reactor at the U.S.G.S. in Denver, receiving a thermal neutron dose of approximately 4.5×10^{-15} neutron/cm^2. The package was allowed to "cool" for 10 days to permit the radioactive decay of short lived nuclides.

After the "cooling" period the apatite packages were mounted as described above. The fossil and induced samples were mounted and were then etched back to back in 7% nitric acid at 25°C for 20-40 seconds.

External detectors were perforated and then removed from their mounts and etched for 13 minutes (Kunk, Michael, 1981, oral communication) in 48% HF at 25°C. Mounts and their detectors were then attached to slides with epoxy, side by side, as mirror images.

The detectors were then removed from the glasses and etched for 1 hour at 25°C in 48% HF. The glasses were then etched in 48% HF at 25°C for 15 seconds.

The glasses and their detectors were then counted at 450X and determination of the neutron dose was done according to procedures of Naeser (1978).

The samples were then counted at 1000X and their ages determined as described above.

RESULTS

Interlaboratory Comparison: Fish Canyon Tuff

As a test of fission track counting procedures and techniques, samples of apatite and zircon from the Fish Canyon Tuff were supplied by Charles Naeser of the U.S.G.S. The samples, previously mounted and irradiated with a known neutron dose, have been used in interlaboratory comparisons of fission track dating, and their ages are well known.

The apatite, dated by the population method, had an age of 26.6 ± 1.0 m.y. (Table 1). This compares favorably with the accepted value of 27.7 ± .97 m.y. (Naeser and Cebula, 1978).

The zircon, dated by the external detector method, had an age of 27.9 ± 1.3 m.y. (Table 1), which also compares favorably to the accepted value of 27.5 ± .23 m.y. (Naeser and Cebula, 1978).

Mineral	# Grains Counted	P_s Tracks 1 cm^2	P_s Tracks	P_i Tracks 1 cm^2	P_i Tracks	Ø Neutrons 1 cm^2	Age m.y.
apatite	50	1.49×10^5	119	3.54×10^5	283	1.053×10^{15}	26.6 ± 1.0
zircon	6	1.24×10^6	116	2.78×10^6	270	1.031×10^{15}	27.9 ± 1.3

$\lambda_F = 6.85 \times 10^{-17} yr^{-1}$

Table 1. Fish Canyon Tuff (72N8) zircon and apatite age determinations.

The standard error of the zircon age was determined using procedures of Johnson and others (1978). The standard error of the apatite age was determined by using procedures of Naeser (1978).

Coronation Island Ages

As shown in Table 2, fission track ages could be determined from only two of seven apatite samples, C4-1, by the external detector method, and C4-4, by the population method. The ages reported in Table 2, 189.4 m.y. and 177.7 m.y., were calculated using the fission-decay constant of $6.85 \times 10^{-17} yr^{-1}$ (Fleischer and Price, 1964a). The neutron doses were determined by counting N.B.S. glasses, SRM 962 and 963, and comparing them with glasses of a known neutron dose. It is necessary to note that due to problems encountered in counting of the glasses, caused by improper polishing, given thermal neutron doses in Table 2 are preliminary. Recounting of the glasses is currently in progress, but the final flux value is not yet available.

The standard of error for sample C4-1 was determined using procedures of Johnson and others (1978). These determinations do not take into account any uncertainties in the neutron dose values.

Samples C-1, C4-2, C4-3, C4-5, and C5-1, as well as the external detector mount of sample C4-4 and the population mounts of sample C4-1, could not be dated by the fission track method due to extremely low track densities and on abundance of impurity, mostly andalusite, in the mount.

Sample Code	Mineral	P_s Tracks 1 cm^2	P_s Tracks	P_i Tracks 1 cm^2	P_i Tracks	∅ Neutron/cm	Age m.y.	# Fields or or Grains
C4-1	apatite	6.09×10^5	39	8.75×10^5	56	4.5×10^{15}	189.4 ± 16.5	15
C4-4	apatite	4.44×10^6	71	6.81×10^6	109	4.5×10^{15}	177.7 ± 12.8	50

$\lambda_F = 6.85 \times 10^{-17} yr^{-1}$

Table 2. Apatite age determinations for samples from Coronation Island.

DISCUSSION

The apatites in this study yielded low track densities, making ages difficult to measure. The presence of low track densities in both the fossil and induced mounts indicate low uranium levels in the rocks, giving measured ages a large uncertainty.

As outlined above, the apatite fission track ages of 189 m.y. and 178 m.y. indicate times when the apatite cooled below approximately 100°C. Considering the uncertainties, these ages are equivalent and consistent with an average of 184 m.y. This age is interpreted to represent regional cooling below 100°C. This probably represents a period of rapid uplift and cooling following the last regional metamorphic event.

The significance of these fission track ages may be viewed with consideration of other isotopic ages. Though no published K-Ar dates from Coronation Island are available, Miller (1960) reported K-Ar ages from Signy Island, also of the South Orkneys, varying from 176-194 m.y. Grikurov and others (1967) reported K-Ar dates, also from Signy Island, varying from 205-235 m.y. Normally, biotite K-Ar dates are considered cooling ages, indicating cooling to about below 300°C in this case, following metamorphic heating. Using 196 m.y. as an average for the K-Ar dates and 184 m.y. as an average for the fission track ages, regional cooling from about 300°C to 100°C took only about 12 m.y. with a cooling rate of about 16°/m.y. Assuming cooling by uplift and erosion and assuming a geothermal gradient of 25°C/km., this translates to roughly 8 km of uplift in 12 m.y. or about 675 m/m.y. or about 0.7 mm/yr. This rate is similar to those observed in the Alps (Wagner and

others, 1977). Again, assuming a 25°C/km geothermal gradient, the surface now exposed must have been less than 4 km deep about 184 m.y. ago. Thus, uplift since then is much slower.

Since doleritic intrusions have been recorded on Coronation Island, this could be a factor affecting track densities in some of the samples. Given the low critical value of track stability of apatite, these intrusions, with contact metamorphism, could have annealled tracks. At present, there are several recorded dikes (Thompson, 1974) near sample locations of C-3 and C4-1 - 5. But precise locations for the dikes were not published and their affects are yet to be determined.

Conclusion

The rocks of Coronation Island cooled to below about 100°C approximately 184 m.y. ago. Uplift and subsequent cooling of these low uranium rocks took about 12 m.y. between closure of the biotite K-Ar system and 100°C. Based upon published K-Ar dates and the new fission track ages, Coronation Island experienced rapid uplift and denudation on the order of 0.7 mm/yr, during the late Triassic.

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